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## THE EFFECTS OF CLOUDS ON CO<sub>2</sub> FORCING

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The cloud radiative forcing (CRF) is the difference between the radiative flux (at the top of the atmosphere, say) which actually occurs in the presence of clouds, and that which would occur if the clouds were removed but the atmospheric state were otherwise unchanged. We also use the term CRF to denote warming or cooling tendencies due to cloud-radiation interactions. Cloud feedback is the change in CRF that accompanies a climate change.

The CO<sub>2</sub> forcing is defined, in analogy with the cloud forcing, as the difference in fluxes and/or infrared heating rates obtained by instantaneously changing the CO<sub>2</sub> concentration (doubling it, say) without changing anything else, i.e. without allowing any feedback. An increased CO<sub>2</sub> concentration leads to a reduced net upward longwave flux at the Earth's surface. This reduced net upward flux is due to an increased downward emission by the CO<sub>2</sub> in the atmosphere above. The negative increment to the net upward flux becomes more intense at higher levels in the troposphere, reaching a peak intensity roughly at the tropopause. It then weakens with height in the stratosphere. This profile implies a warming of the troposphere and cooling of the stratosphere.

The CO<sub>2</sub> forcing has been evaluated in the past using highly simplified models (e.g., Ramanathan *et al.*, 1979), but it is nevertheless highly desirable to evaluate it using GCMs, for two reasons: First, the GCMs take into account many more geographical and temporal variations, so that they can be expected to give more accurate and realistic results; and second, the CO<sub>2</sub> forcing should be determined using the same computational tool that is used to predict the response to the forcing, i.e. the GCM itself.

The CSU GCM has recently been used to make some preliminary CO<sub>2</sub> forcing calculations, for a single simulated, for July conditions. We called the longwave radiation routine twice, to determine the radiative fluxes and heating rates for both 2 x CO<sub>2</sub> and 1 x CO<sub>2</sub>. As diagnostics, we have saved the two-dimensional distributions of the longwave fluxes at the surface and the top of the atmosphere, as well as the three-dimensional distribution of the longwave cooling in the interior. In addition, we have saved the pressure (near the tropopause) where the difference in the longwave flux due to CO<sub>2</sub> doubling has its largest magnitude. For convenience, we refer to this level as the "CO<sub>2</sub> tropopause". We have also saved the actual difference in the flux at that level. Finally, we have duplicated all of these fields for the hypothetical case of no cloudiness (clear sky), so that we can isolate the effects of the clouds.

Fig. 1 shows the zonally averaged net upward longwave flux difference due to a doubling of CO<sub>2</sub>, at three levels: the Earth's surface, the CO<sub>2</sub> tropopause, and the top of the atmosphere (where  $p = 0$ ). All of the numerical values are negative, since doubling CO<sub>2</sub> reduces the net upward flux at every level. At the Earth's surface, the CO<sub>2</sub> forcing reduces the net upward flux by about 2 W m<sup>-2</sup> in high latitudes, where there is little water vapor, but by only about 0.5 W m<sup>-2</sup> near the equator, where the lower troposphere is very humid and therefore relatively opaque in the infrared. The flux reductions at the CO<sub>2</sub> tropopause and the top of the atmosphere are not very

different from each other; this means that the flux difference across the stratosphere is relatively small (on the order of  $0.5 \text{ W m}^{-2}$ ), but since the stratosphere contains much less mass than the troposphere, the stratospheric cooling and tropospheric warming can be of comparable magnitude, as we will see below. The flux reduction at the top of the atmosphere reaches about  $5 \text{ W m}^{-2}$  in the tropics, where the lower boundary is relatively warm, and is near  $4 \text{ W m}^{-2}$  at the summer pole, and near  $2 \text{ W m}^{-2}$  at the winter pole. It has a dip near the equator, which is due to the presence of extensive upper tropospheric cloudiness in the intertropical convergence zone (ITCZ). The clouds block the upwelling tropospheric radiation anyway, so that increasing the  $\text{CO}_2$  concentration has relatively little effect. These cloud effects are discussed further later.

Fig. 2 shows the changes in the longwave heating of the troposphere and the longwave cooling of the stratosphere (both plotted as positive values, for convenience), in units of hundredths of a degree per day. The tropospheric warming peaks at more than  $0.05 \text{ K day}^{-1}$  in the tropics, where the downwelling infrared flux due to emission by warm  $\text{CO}_2$  converges almost entirely within the humid atmosphere, so that very little reaches the surface (refer back to Fig. 1). The tropospheric warming is relatively weak in high latitudes, where the atmosphere is relatively dry. The stratospheric cooling is between  $1.0$  and  $1.5 \text{ K day}^{-1}$ , almost independent of latitude.

Fig. 3 shows the effects of clouds on the  $\text{CO}_2$  forcing, in terms of the reduction in the net upward infrared flux at the surface, the  $\text{CO}_2$  tropopause, and the top of the atmosphere. For the Earth's surface (solid line), a positive value on this plot indicates that the clouds act to reduce the  $\text{CO}_2$  forcing of the surface. The largest positive values occur in high latitudes, where there are extensive low clouds that block the downward radiation due to  $\text{CO}_2$  emission from the atmosphere. The tropical atmosphere contains so much water vapor that the clouds have relatively little effect; at any rate, the tropical clouds tend to have their bases in the middle troposphere, further away from the surface. The effects of the clouds on the  $\text{CO}_2$  forcing at the  $\text{CO}_2$  tropopause and the top of the atmosphere are practically the same, since the stratosphere is essentially cloudless. Again, positive values for the dashed and dotted curves indicate that the clouds tend to mitigate the reduction in the net upward longwave flux due to doubling  $\text{CO}_2$ . Where the solid curve lies above the dashed/dotted curves, the clouds increase the  $\text{CO}_2$  forcing of the troposphere. This occurs in high latitudes, where the clouds are found at low levels. Where the solid curve lies below the dashed/dotted curves, the clouds reduce the  $\text{CO}_2$  warming of the troposphere. This occurs in the tropics and the middle latitudes of the summer hemisphere, where high clouds block the upwelling longwave radiation anyway.

Fig. 4 shows the latitude-height distribution of the  $\text{CO}_2$  forcing, in hundredths of a degree per day. The tropospheric warming is most intense near the surface in the tropics, reaching about  $0.16 \text{ K day}^{-1}$ . There is actually a weak cooling at low levels in high latitudes, where temperature inversions occur near the surface. Recall that the  $\text{CO}_2$  tropopause is defined as the level where the  $\text{CO}_2$ -induced reduction in the net upward longwave flux is most intense; it separates tropospheric warming from stratospheric cooling. Fig. 4 shows that the height of the  $\text{CO}_2$  tropopause is about  $12 \text{ km}$ , at all latitudes. There is a minor excursion to higher altitudes just north of the equator, due to the upper tropospheric cloudiness associated with deep convection in the ITCZ. Finally, Fig. 5 shows the effects of clouds in Fig. 4. The clouds tend to reduce the warming in the tropical and summer-hemisphere troposphere, and to increase it in the middle and high-latitude troposphere. They tend to increase the warming near the tropical tropopause, and to reduce the stratospheric cooling slightly.

Two strong caveats are needed here. First, these results are for a single day. They do not show how the  $\text{CO}_2$  forcing varies diurnally or seasonally; we plan to investigate such diurnal and seasonal changes in the future. Second, these results tell nothing about how the climate system

will respond to the CO<sub>2</sub> forcing, since that response depends strongly on feedbacks within the system.

## ACKNOWLEDGEMENTS

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## REFERENCES

Ramanathan, V., M. S. Lian, and R. D. Cess, 1979: Increased atmospheric CO<sub>2</sub>: Zonal and seasonal estimates of the effect on the radiation energy balance and surface temperature. *J. Geophys. Res.*, **84**, 4949-4958.

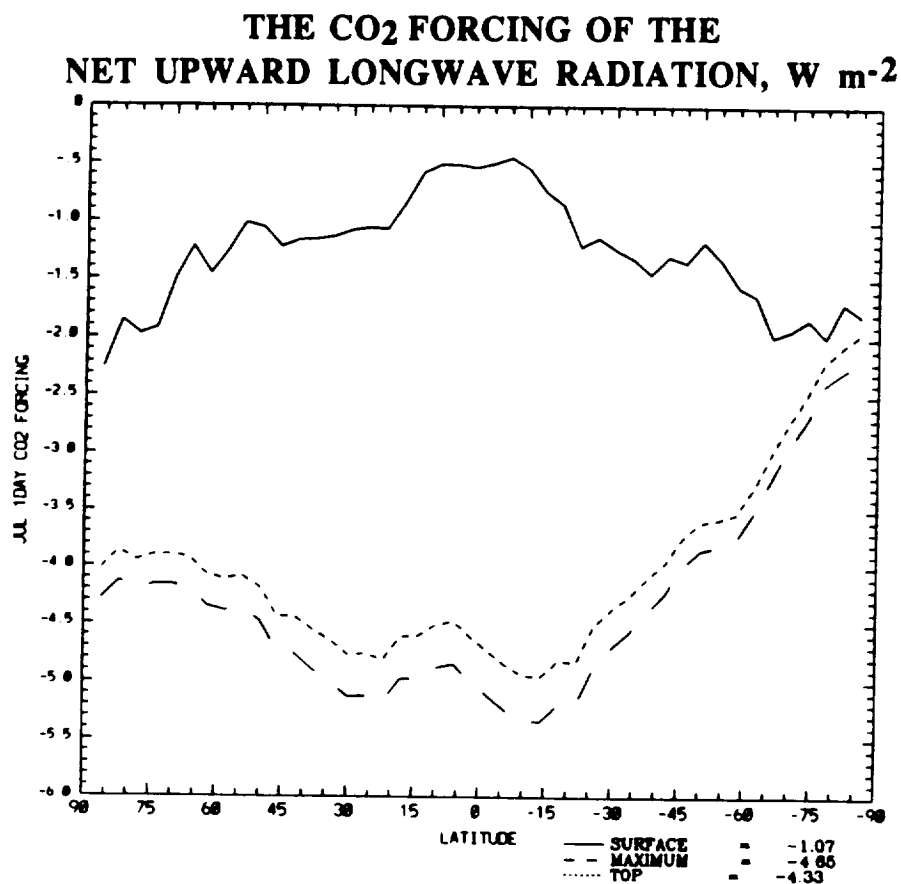


Figure 1

**THE EFFECTS OF CO<sub>2</sub>  
ON THE TROPOSPHERIC WARMING  
AND STRATOSPHERIC COOLING, 0.01 K day<sup>-1</sup>**

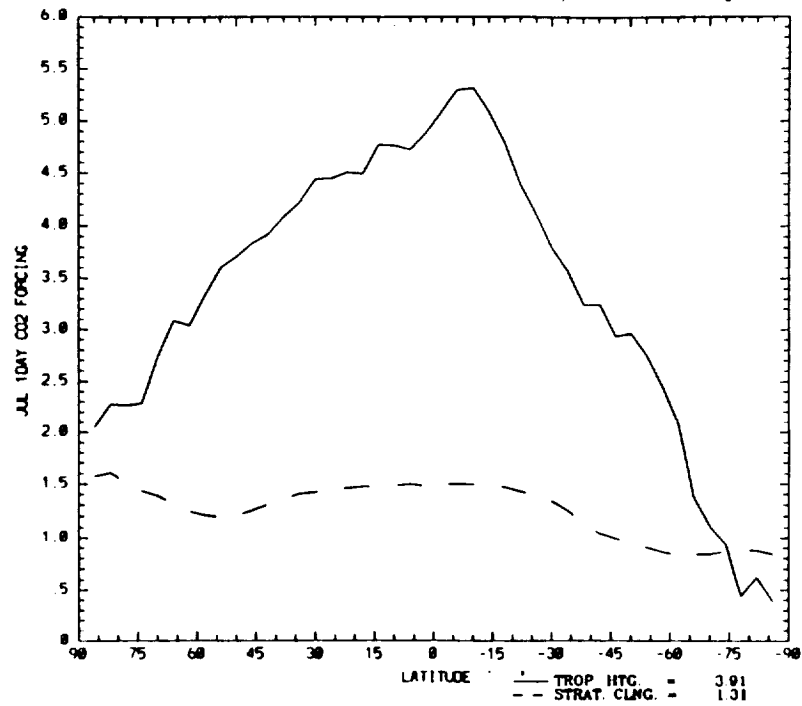


Figure 2

**THE EFFECTS OF CLOUDS ON THE CO<sub>2</sub> FORCING OF THE  
NET UPWARD LONGWAVE RADIATION, W m<sup>-2</sup>**

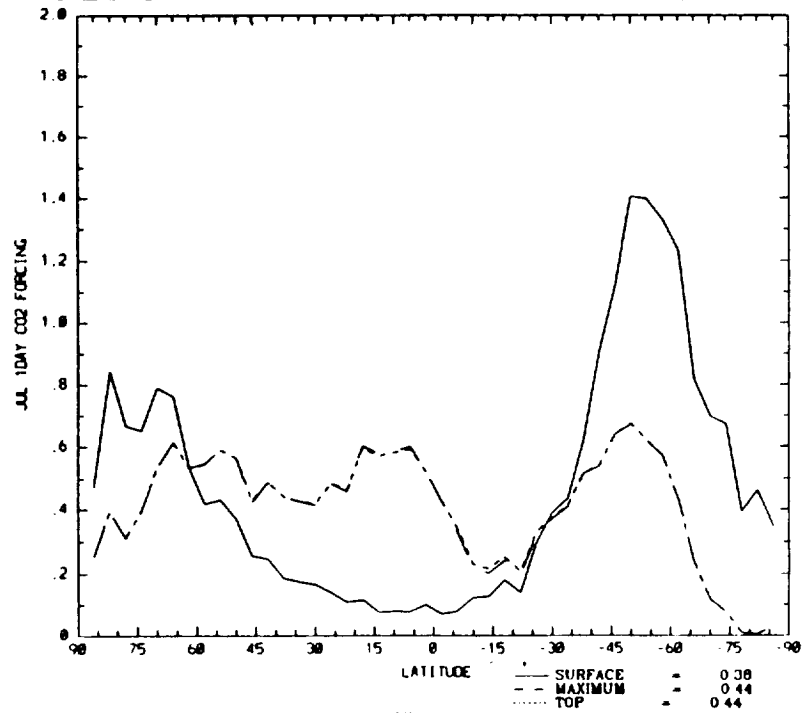


Figure 3

# THE CO<sub>2</sub> FORCING, 0.01 K day<sup>-1</sup>

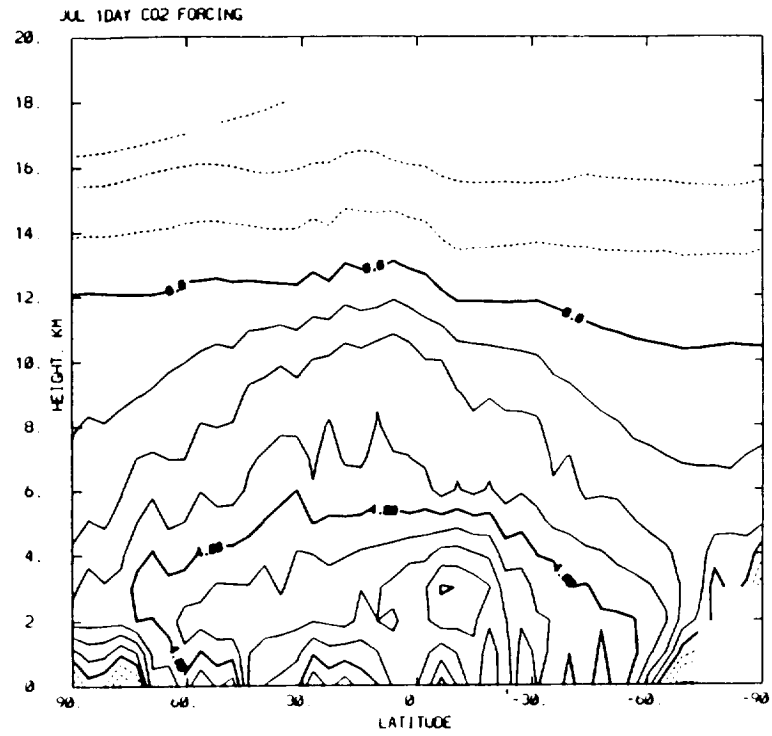


Figure 4

# THE EFFECTS OF CLOUDS ON THE CO<sub>2</sub> FORCING, 0.01 K day<sup>-1</sup>

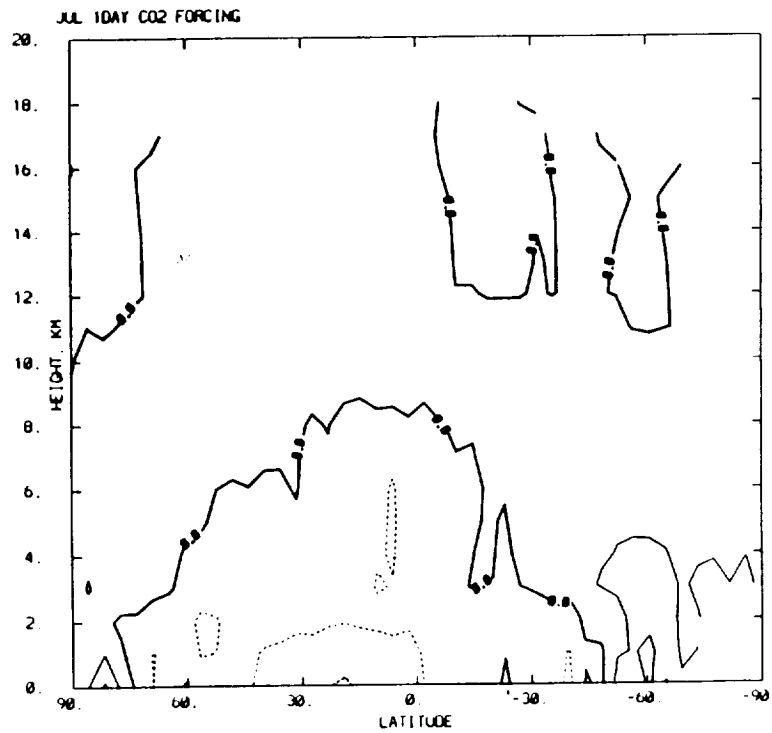


Figure 5

## FIGURE CAPTIONS

- Figure 1: The meridional structure of the zonally averaged net upward longwave flux difference due to a doubling of CO<sub>2</sub>, at the Earth's surface (solid line), the CO<sub>2</sub> tropopause (long dashes), and the top of the atmosphere (short dashes).
- Figure 2: The meridional structure of the CO<sub>2</sub>-induced changes in the zonally averaged longwave heating of the troposphere (solid line) and the zonally averaged longwave cooling of the stratosphere (dashed line), both plotted as positive values, for convenience, in units of hundredths of a degree per day.
- Figure 3: The effects of clouds on the CO<sub>2</sub> forcing, in terms of the reduction in the net upward infrared flux at the surface (solid line), the CO<sub>2</sub> tropopause (long dashes), and the top of the atmosphere (short dashes). The units are W m<sup>-2</sup>.
- Figure 4: The latitude-height distribution of the CO<sub>2</sub> forcing, in hundredths of a degree per day.
- Figure 5: The effects of clouds on the latitude-height distribution of the CO<sub>2</sub> forcing, in hundredths of a degree per day.